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SOIL-MOISTURE CONSTANTS AND THEIR VARIATION

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CONTENTS

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"Constants" like field capacity, liquid limit, moisture equivalent, and wilting point are used by most students and workers in soil moisture. These constants may be equilibrium points or other values that describe soil moisture. Their values under specific soil and cover conditions have been discussed at length in the literature, but few general analyses and comparisons are available.

During the past several years the Vicksburg Research Center[1] of the Southern Forest Experiment Station has been accumulating information on effects that physical properties have on soil hydrology. The work has included an extensive review of literature in addition to field studies on many sites throughout the United States, Alaska, and Puerto Rico. Values were secured for most recognized constants.

This paper summarizes the data gathered in the library and the field. The authors believe that it may be a useful reference for other researchers. For students, it may illustrate the fact that soil-moisture constants, far from being fixed, vary considerably with the physical condition of the soil.

Some explanation is due of the procedure followed in compiling the information, together with some precautions as to its use. The data are from 901 samples of surface soil and 400 samples of subsoil. Data from published sources were combined with those obtained in studies at the Vicksburg Research Center.

This procedure raised some difficulties, one being that of citing sources. Because data from published sources lost their identity upon being tabulated, no attempt was made to cite references for specific observations. All published sources, however, are included in the bibliography (p. 23). Published material was accepted at face value, as it was assumed that procedures used in obtaining it were standard though not necessarily identical.

Most surface soil samples were from depths of 0 to 6 inches, but some samples were as much as 36 inches deep. Thick layers, when reported in the literature as surface soils, were assumed to be uniform in

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[1] Maintained at Vicksburg, Mississippi, by the Southern Forest Experiment Station, Forest Service, U. S. Department of Agriculture, in cooperation with the Waterways Experiment Station, Corps of Engineers, U.S. Army.

moisture values and other properties. Subsoil samples were those indicated in published material as being from the B horizon or below, or (especially in the sampling at Vicksburg) from depths greater than 6 inches.

The number of observations, although seemingly large, provided too little data for some comparisons. Consequently only the most commonly used constants are represented. Values for the sandy clay and silt textural classes often had to be omitted entirely.

The first values to be discussed are those relating moisture to soil texture, land use, and aeration. Later sections discuss ways of predicting bulk density, and "wet" and "dry" values from other soil properties. Finally, results from four methods of estimating available water are tabulated and briefly discussed. The tables generally include the number of observations on which the average value is based, the average value for the relation, and the standard deviation of the mean.

EXPLANATION OF TERMS AND SYMBOLS

The following symbols and definitions have been adhered to throughout this report. For the most part they follow general practice, but the soil properties that were used in the regression analyses are represented by two symbols. The first is the abbreviation that appears in many of the charts and tables (as S, BD), the second designates the property in the regression analysis (as X_1, X_2).

0.1-atmosphere moisture (0.1-atm). Moisture content of a soil that has been saturated and then brought to equilibrium at pressure of 0.1 atmosphere.

1/3-atmosphere moisture (1/3-atm). Moisture content of a soil that has been saturated and then brought to equilibrium at a pressure of 1/3 atmosphere.

15-atmospheres moisture (15-atm). Moisture content of a wetted soil after reaching equilibrium at a pressure of 15 atmospheres.

60-cm moisture (60-cm). Moisture content of an undisturbed soil core that has been saturated and then brought to equilibrium at 60 cm of water tension.

Available water capacity, calculated by one of these methods:
60-cm value minus 15-atm value
1/3-atm value minus 15-atm value
Field capacity minus wilting point
Field maximum minus field minimum.

Big pores (BP) (X_4). That pore volume reported in the literature as big pores, non-capillary pores, or readily drained pores; or that volume obtained by subtracting the 60-cm water-tension value from the total pore volume of a sample.

Bulk density (BD) (X_5). Ratio of the weight of dry soil to the volume it occupied in the field, expressed as grams per cubic centimeter.

Drainage capacity (DC) (X_7). That volume of a sample representing the difference in total pore volume and volume of water held at 1/3-atmosphere pressure.

Field capacity (FC). Field moisture content of well-drained soils approximately two days after saturation.

Field maximum (F max) (X_8). Maximum recurring average moisture content of a soil *in situ*.

Field minimum (F min) (X_9). Minimum recurring moisture content of a soil *in situ*.

Field moisture index (FMI) (X_{10}). Field maximum moisture content minus the field minimum moisture content.

Liquid limit (LL) (X_{12}). Moisture content in percent by weight at which a soil will barely flow under an applied force.

Moisture equivalent (ME). Moisture content of a soil subjected to a force of approximately 1,000 x gravity.

Organic matter (OM) (X_3). Organic content expressed as percent by weight.

Plastic limit (PL) (X_{11}). Moisture content in percent by weight at or above which a soil will puddle if handled or worked.

Saturation (0-5 cm). Moisture content of a soil core that has been saturated and then brought to 0-5 cm of water tension.

Saturation percentage. Moisture content of a sample of soil that has been brought to saturation by adding water while stirring.

Soil separates
Clay (C) (X_2). Percent by weight.
Sand (S) (X_1). Percent by weight.
Silt (Si) (X_6). Percent by weight.

Soil texture classes
Clay loam (CL)
Loam (L)
Loamy sand (LS)
Sandy clay (SC)
Sandy clay loam (SCL)
Sandy loam (SL)
Silt loam (SiL)
Silty clay (SiC)
Silty clay loam (SiCL)

Total pore volume. Percent by volume of total pore space of a sample as calculated from bulk density and specific gravity for soils with less than 10 percent organic matter, or the value as reported in the literature references.

Water-holding capacity. Moisture content of a soil core or disturbed column of soil after it has drained following saturation.

Wilting point (WP). Moisture content of a soil when plants growing in it wilt permanently.

Average values of mechanical composition were calculated for each texture class defined by the Soil Survey Manual of the U.S. Department of Agriculture (Agriculture Handbook 18). Results are shown in figure 1. Most averages were well centered within the class, except that the clay soils were somewhat lower than average in clay content and higher in silt.

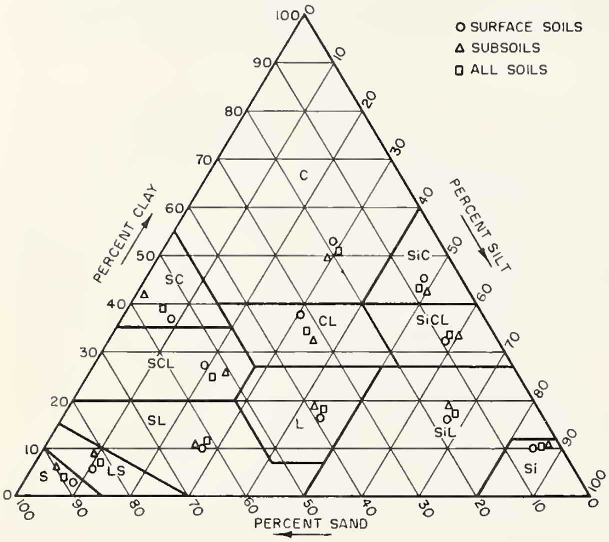

Figure 1.--*Average textural composition of the samples used in relating soil-moisture constants to texture.*

Soil-moisture constants vary considerably with change of texture. Table 1 and figure 2 summarize the relative moisture values of the most common textural classes, as arranged in approximate order of grain size. In general, values averaged lower for the sandy soils.

Field maximums in the sand, loamy sand, and sandy loam classes were more closely approached by the 60-centimeter values than by the

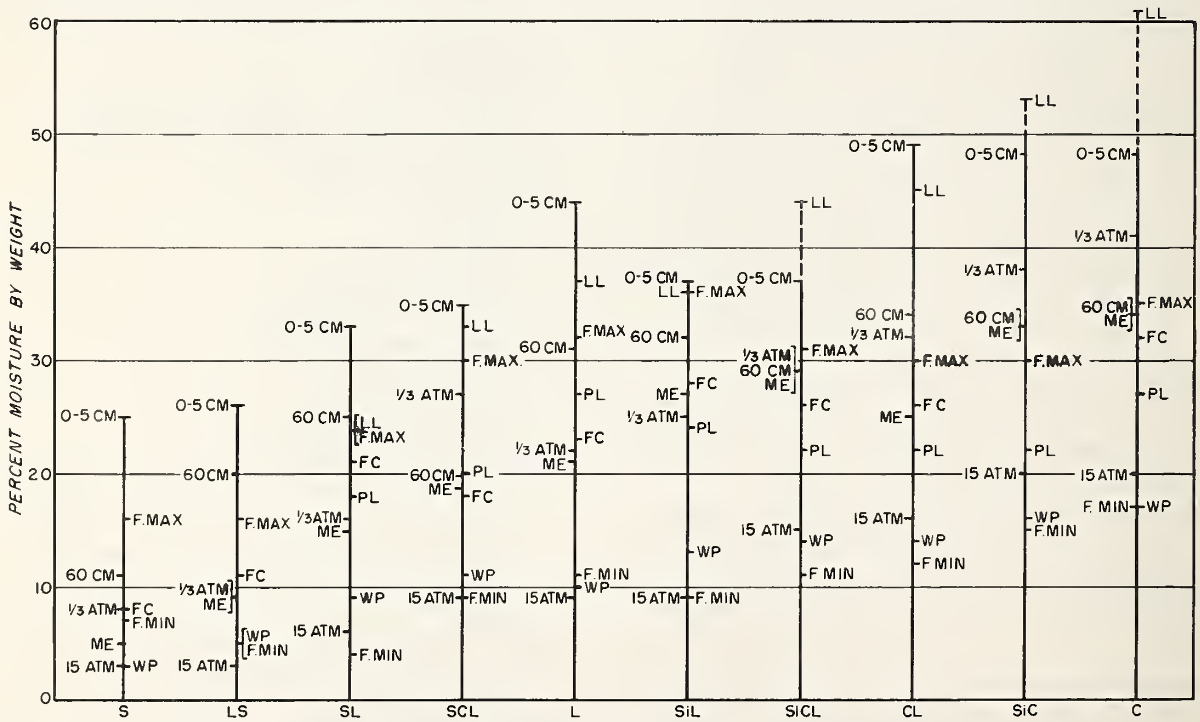

Figure 2.--*Moisture values of various textural classes of surface and subsoils.*

Table 1. --Moisture constants, by weight, for various textural classes

Soil-moisture constant	Soil textural class									
	S	LS	SL	SCL	L	SiL	SiCL	CL	SiC	C
0-5 cm										
N[1]	19	10	10	2	21	104	13	8	8	8
$\bar{X}$[2]	25	26	33	35	44	37	37	49	48	48
s[3]	5.2	7.4	9.7	18.4	15.7	11.6	14.3	16.6	20.1	15.1
F max										
N	4	2	32	5	30	92	16	8	5	16
$\bar{X}$	16	16	24	30	32	36	31	30	30	35
s	3.7	2.8	10.1	8.0	8.7	12.5	4.8	6.1	9.9	8.4
60-cm										
N	9	3	14	4	33	111	19	7	7	11
$\bar{X}$	11	20	25	20	31	32	29	34	33	34
s	7.4	5.0	7.4	4.0	10.9	10.6	5.4	9.3	7.3	6.5
0.1-atm.										
N	15	10	5	2	13	59	2	7	3	4
$\bar{X}$	7	12	20	30	26	35	47	40	49	35
s	2.1	5.2	6.6	10.6	8.2	11.5	12.7	10.2	6.0	7.9
FC										
N	2	9	40	3	12	29	13	11	...	56
$\bar{X}$	8	11	21	18	23	28	26	26	...	32
s	2.8	3.2	5.9	2.6	3.0	7.4	2.6	5.0	...	4.8
1/3-atm.										
N	12	10	26	2	24	102	16	11	6	19
$\bar{X}$	8	9	16	27	22	25	29	32	38	41
s	1.9	4.5	6.0	12.7	5.7	7.7	5.9	7.3	8.4	12.3
ME										
N	28	29	131	14	103	186	53	32	15	83
$\bar{X}$	5	9	15	19	21	27	29	25	33	34
s	3.2	4.9	5.2	6.2	5.0	6.9	4.2	5.5	5.8	8.9
15-atm.										
N	23	17	51	8	52	162	27	21	9	47
$\bar{X}$	3	3	6	9	9	9	15	16	20	20
s	1.8	1.9	2.9	2.6	4.6	3.6	2.4	4.4	9.6	5.7
WP										
N	7	19	38	3	33	46	33	20	4	64
$\bar{X}$	3	5	9	11	10	13	14	14	16	17
s	3.1	2.5	3.4	5.0	3.7	4.9	3.1	4.2	2.8	2.9
F min										
N	4	2	21	5	25	88	22	10	9	14
$\bar{X}$	7	5	4	9	11	9	11	12	15	17
s	.6	.0	2.9	5.0	6.4	3.5	2.7	2.2	2.6	4.7
LL										
N	...	...	14	4	25	119	27	9	10	17
$\bar{X}$	...	...	24	33	37	36	44	45	53	61
s	...	...	4.6	6.2	10.7	8.8	6.7	6.8	9.9	15.1
PL										
N	...	...	14	4	25	118	26	8	10	15
$\bar{X}$	...	...	18	20	27	24	22	22	22	27
s	...	...	4.2	4.5	8.8	5.6	2.5	2.1	5.9	5.7

[1] Number of samples.
[2] Mean.
[3] Standard deviation.

moisture-equivalent and 1/3-atmosphere values. In fine soils the 1/3-atmosphere and moisture-equivalent values were about as high as the 60-centimeter readings, possibly because they were determined from disturbed or bulk samples whereas the 60-centimeter values were from undisturbed soil cores.[2]

In coarse soils, the 15-atmosphere and wilting-point values were as small as 3 percent by weight. In the fine soils, there was a definite and consistent tendency for 15-atmosphere values to be higher than other "dry end" constants. In all fine soils, wilting point and field minimum were very close together.

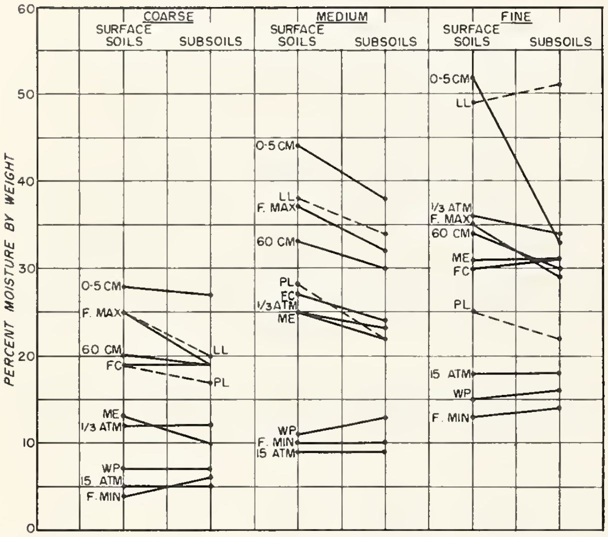

Figure 3.--*Average moisture constants, by weight, for coarse, medium, and fine soils.*

Additional examination was made with moisture values grouped by coarse, medium, and fine textural classes. The grouping of the twelve classes was as follows: (1) coarse, consisting of sand, loamy sand, and sandy loam; (2) medium, consisting of loam, silt loam, sandy clay loam, sandy clay, and silt; (3) fine, consisting of silty clay loam, clay loam, silty clay, and clay. Values are shown on a percent-by-weight basis in table 2 and figure 3. Both surface and subsoil data for each of the three groups are given. To facilitate comparison, the moisture values in figure 3 for surface and subsoils are shown connected by lines.

For coarse-textured soils, moisture content at field capacity and 60-centimeter tension were about equal (approximately 20 percent) for both surface and subsoils. Field-maximum values were about 5 percent higher than the 60-centimeter and field-capacity values in the surface layers but were about equal to them in the subsoils. Moisture-equivalent and 1/3-atmosphere values were considerably lower than field capacity in the coarse-textured soils. The moisture content at which these soils puddled was only slightly less than field-capacity or 60-centimeter water tension.

In the medium textural group, field capacity, 1/3-atmosphere moisture, moisture equivalent, and plastic limit are closely bunched at about 26 percent in the surface soils and 23 percent in the subsoils. The 60-centimeter moisture constant is higher by 6 to 7 percent in both surface and subsoils.

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[2] Broadfoot, W.M. *Core vs. bulk samples in soil-moisture tension analysis. In* SOME FIELD, LABORATORY, AND OFFICE PROCEDURES FOR SOIL-MOISTURE MEASUREMENT. U.S. Forest Serv. South. Forest Expt. Sta. Occas. Paper 135, pp. 22-25. 1954.

Table 2.--Moisture constants, by weight, of coarse, medium, and fine soils

Textural composition and moisture constant	Surface soils			Subsoils			All soils		
	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation
	No.	- Percent -		No.	- Percent -		No.	- Percent -	
COARSE TEXTURE									
Sand	94	68	13.0	42	71	12.9	136	69	12.9
Silt	80	23	11.1	41	20	10.9	121	22	11.1
Clay	96	9	5.0	42	9	4.5	138	9	4.9
LL	10	25	4.4	4	20	2.1	14	24	4.6
PL	10	19	4.9	4	17	1.4	14	18	4.2
0-5 cm	30	28	8.7	9	27	3.3	39	28	7.7
F max	26	25	11.1	12	19	4.0	38	23	9.8
60-cm	17	20	8.2	9	19	12.0	26	20	9.4
0.1-atm	25	11	6.6	5	8	3.1	30	11	6.3
FC	41	19	6.8	10	19	7.8	51	19	6.9
1/3-atm	37	12	6.6	11	12	5.8	48	12	6.4
ME	151	13	6.1	37	10	4.9	188	12	6.0
15-atm	72	5	2.5	19	5	2.5	91	5	2.5
WP	51	7	3.6	13	7	5.0	64	7	3.9
F min	17	4	1.6	10	6	3.7	27	5	2.6
MEDIUM TEXTURE									
Sand	158	28	14.7	138	26	15.0	296	27	14.8
Silt	154	56	14.7	138	55	16.1	292	56	15.4
Clay	160	16	6.2	138	19	6.2	298	17	6.3
LL	64	38	9.6	86	34	8.5	150	36	9.1
PL	63	28	6.2	86	22	5.2	149	25	6.3
0-5 cm	78	44	11.2	50	38	13.4	128	42	12.4
F max	71	37	12.2	59	32	10.8	130	35	11.8
60-cm	76	33	10.8	74	30	10.7	150	32	10.8
0.1-atm	51	35	10.6	24	30	13.8	75	33	11.8
FC	34	27	7.2	12	24	5.5	46	26	6.9
1/3-atm	83	25	8.0	47	23	6.7	130	24	7.6
ME	225	25	7.2	89	22	5.3	314	24	6.9
15-atm	135	9	3.9	92	9	3.4	227	9	3.8
WP	56	11	4.9	34	13	4.3	90	12	4.7
F min	66	10	5.4	54	10	3.7	120	10	4.7
FINE TEXTURE									
Sand	49	17	11.6	69	15	11.9	118	16	11.7
Silt	47	42	14.6	68	48	14.4	115	45	14.6
Clay	54	41	11.6	70	37	8.5	124	39	10.1
LL	20	49	11.2	43	51	12.8	63	50	12.2
PL	18	25	5.7	41	22	3.9	59	23	4.7
0-5 cm	21	52	17.2	16	33	6.5	37	44	16.5
F max	23	35	6.7	22	29	6.4	45	32	7.2
60-cm	18	34	7.2	26	30	6.1	44	32	6.8
0.1-atm	14	43	9.5	2	31	5.7	16	41	9.9
FC	67	30	5.6	13	31	3.9	80	30	5.4
1/3-atm	27	36	11.2	25	34	9.6	52	35	10.4
ME	132	31	8.3	51	31	6.3	183	31	7.8
15-atm	49	18	6.1	53	18	4.3	104	18	5.2
WP	90	15	3.3	31	16	4.2	121	16	3.6
F min	29	13	4.0	26	14	3.8	55	13	3.9

The plastic limit for the fine-textured soils occurred about midway between field capacity and wilting point, or when approximately 50 percent of available water was present.

Wilting-point, field-minimum, and 15-atmosphere values are about 5 percent for the coarse-textured soils, 10 percent for medium-textured soils, and 15 percent for fine-textured soils. The field-minimum and wilting-point values are less than the 15-atmosphere value in the fine soils.

Soil moisture in percent by volume is shown in table 3 and figure 4. The values are similar to those calculated on a weight basis, but are not necessarily from the same set of samples.

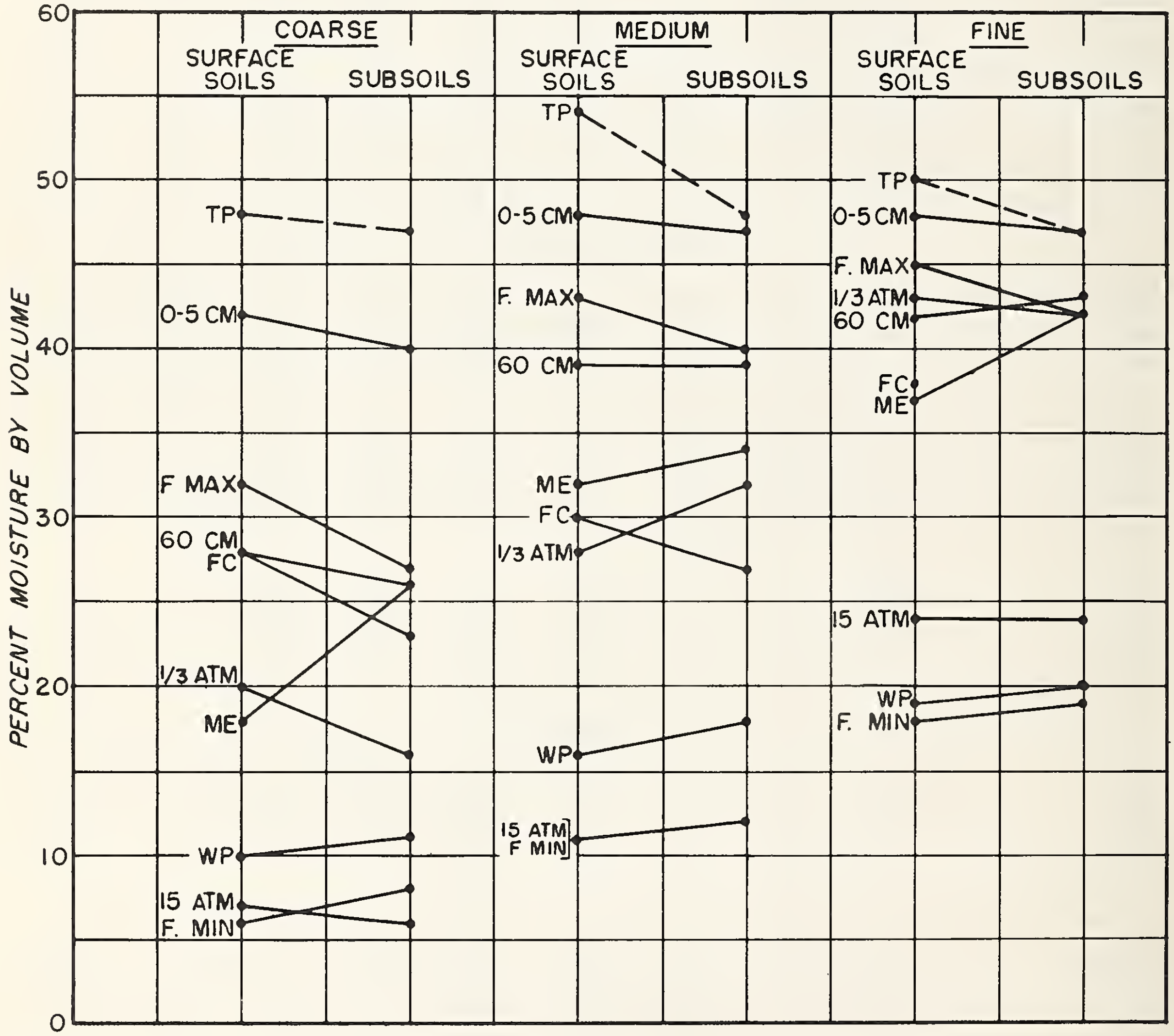

Figure 4.--*Average moisture constants, by volume, for coarse, medium, and fine soils.*

Table 3. --Moisture constants, by volume, of coarse, medium, and fine soils

Total pore volume and moisture constant	Surface soils			Subsoils			All soils		
	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation
	No.	- Percent -		No.	- Percent -		No.	- Percent -	
COARSE TEXTURE									
Total pores	79	48	7.0	20	47	6.2	99	47	6.8
0-5 cm	14	42	5.2	8	40	3.7	22	41	4.8
F max	26	32	9.6	12	27	8.8	38	30	9.5
60-cm	14	28	9.9	9	26	13.7	23	27	11.2
0.1-atm	7	20	10.8	4	12	5.9	11	17	9.9
FC	14	28	7.7	5	23	2.4	19	26	7.0
1/3-atm	17	20	9.1	10	16	6.8	27	19	8.4
ME	46	18	7.1	2	26	7.8	48	18	7.2
15-atm	28	7	3.2	14	6	3.4	42	7	3.2
WP	12	10	3.4	3	11	.7	15	11	3.0
F min	16	6	2.1	10	8	3.6	26	7	2.9
MEDIUM TEXTURE									
Total pores	195	54	6.4	124	48	7.6	319	51	7.4
0-5 cm	50	48	7.4	50	47	8.6	100	47	8.0
F max	69	43	6.8	59	40	7.2	128	42	7.1
60-cm	74	39	7.1	74	39	6.6	148	39	6.8
0.1-atm	24	33	7.1	24	36	9.1	48	34	8.2
FC	21	30	6.5	9	27	3.9	30	29	6.0
1/3-atm	48	28	7.4	44	32	5.7	92	30	6.9
ME	98	32	5.5	22	34	6.0	120	38	5.6
15-atm	86	11	3.9	86	12	4.5	172	12	4.3
WP	25	16	6.1	18	18	4.5	43	17	5.5
F min	55	11	5.4	54	12	5.1	109	12	5.2
FINE TEXTURE									
Total pores	50	50	6.0	52	47	6.0	102	48	6.2
0-5 cm	8	48	6.7	16	47	7.3	24	48	7.0
F max	20	45	4.0	22	42	7.0	42	43	5.9
60-cm	12	42	5.5	26	43	7.2	38	43	6.7
0.1-atm	1	51	.0	2	42	6.4	3	45	6.7
FC	4	38	11.3	...	...	...	4	38	11.3
1/3-atm	9	43	16.6	15	42	7.1	24	43	11.3
ME	30	37	7.0	12	42	6.9	42	38	7.3
15-atm	16	24	6.8	36	24	6.5	52	24	6.5
WP	17	19	4.2	7	20	1.4	24	20	3.1
F min	19	18	4.6	17	19	7.7	36	18	6.2

Data representing known land-use conditions were grouped into three categories: forest, old field, and pasture.

The forest category was comprised of all soils supporting a moderately well-stocked stand of trees, whether or not the soils were virgin. Some of the samples were from 10- to 15-year-old pine plantations on abandoned farm land. These sites were classed as forest because only the surface layer was sampled, and it was felt that the trees had had enough time to influence this layer.

The old-field category included only former cultivated fields that had herbaceous cover at the time of sampling and were not grazed. Grazed old fields, as well as grazed woodland, were included in the pasture category.

The surface soils under forest had better structure than either the old-field or pasture soils (table 4, figure 5).

Table 4.--Porosity and moisture constants, by volume, for surface soils under different land uses

Total porosity and moisture constant	Forest			Old field			Pasture		
	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation
	No.	- Percent -		No.	- Percent -		No.	- Percent -	
Total pores	67	56	8	72	50	7	47	51	6
0-5 cm	22	47	9	13	45	4	23	46	6
F max	24	36	9	33	41	6	25	43	8
60-cm	33	36	8	21	37	5	33	41	6
1/3-atm	22	22	8	20	32	10	19	28	8
ME	25	24	10	30	32	8	12	36	4
15-atm	38	8	4	52	15	8	34	14	6
F min	22	8	4	25	13	6	23	12	6

Total pore volume was 56 percent in the forest soils, 50 percent in the old fields, and 51 percent in the pasture soils. Inclusion of the grazed woodland soils in the pasture category probably increased the average porosity to that of old fields.

At field maximum and 60-centimeter tension, which represent wet condition or water-holding capacity, soils in all three categories were close together, but the forest soils had the most space for further absorption of water (as indicated in figure 5 by the difference between the 60-cm and 0-5 cm value--roughly the volume of big pores). The additional space amounted to about 11 percentage points, that is, 0.11 inch of water per inch of soil under forests as compared to about 0.08 inch in old field and 0.05 inch in

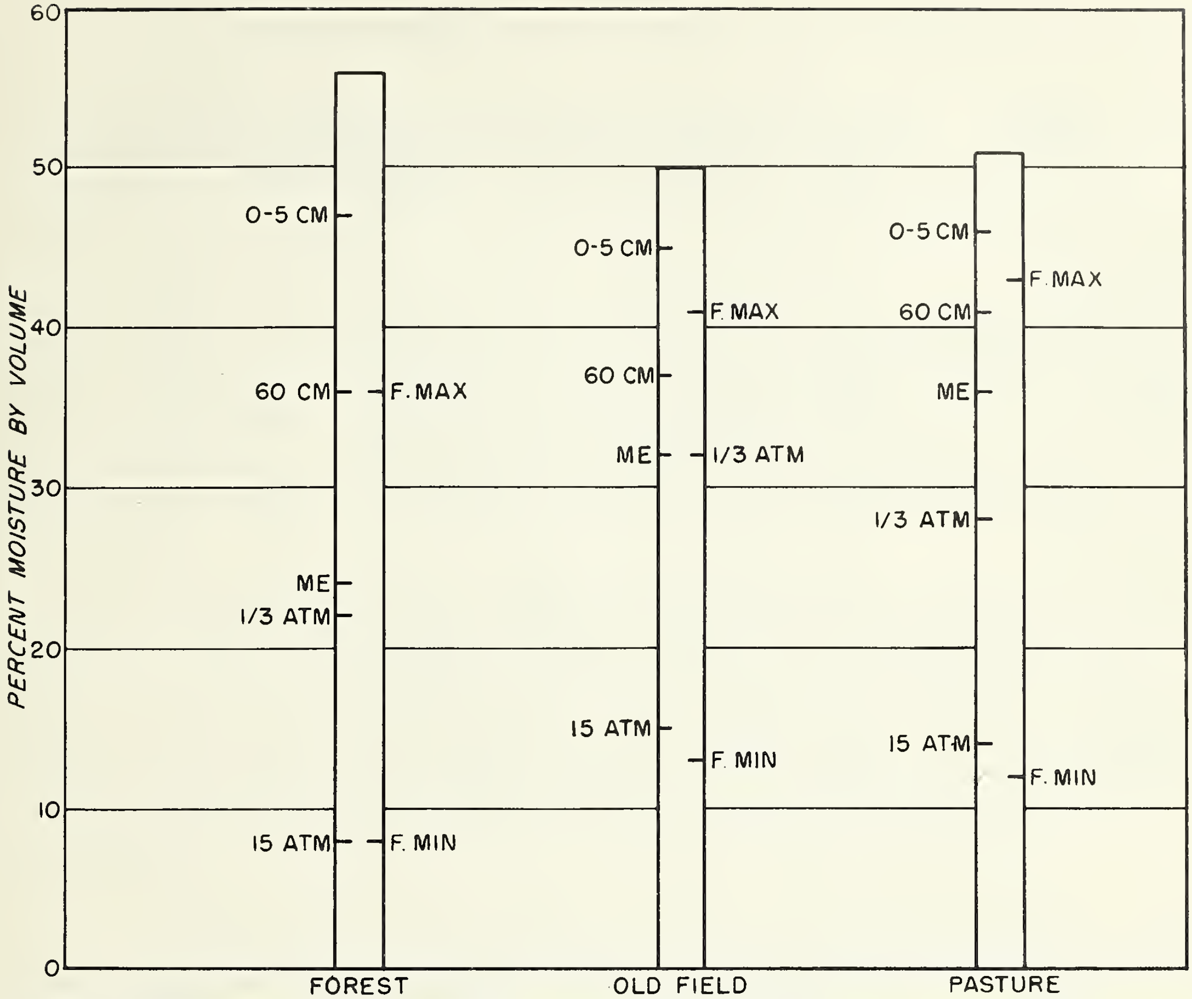

Figure 5.--*Average moisture constants of surface soils in forests, old fields, and pastures. Total pore volume is indicated by the height of the bars.*

pastures. This comparison would indicate that, in the surface 12 inches, the forest soils could absorb about 1/2-inch more rain than the pasture and old-field soils.

The degree of soil aeration, as measured by the amount of big pores, is an important criterion in estimating plant-soil-water relationships. On well-drained sites, soils with considerable volume of big pores empty quickly after saturation and permit entry of air. Another commonly used index of aeration is drainage capacity. The relationships of big-pore volume and drainage capacity to soil texture and land use are shown in tables 5 and 6. Both properties seem well correlated with texture. Surface soils had consistently more big-pore volume and higher drainage capacity than subsoils.

The influence of land use is also apparent, in that forest soils have substantially more big pores and greater drainage capacity than old-field or pasture soils. Cultivation and trampling by livestock are probably responsible for the differences.

Table 5.--Average volume of big pores, by textural groups and land-use categories

Textural group and land use	Surface soils			Subsoils			All soils		
	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation
	No.	- Percent -		No.	- Percent -		No.	- Percent -	
Textural group									
Sand	5	30	8	4	31	6	9	30	7
Loamy sand	5	17	12	1	9	0	6	16	11
Sandy loam	27	16	9	6	14	7	33	16	9
Average for coarse soils	37	18	10	11	20	11	48	18	10
Sandy clay loam	3	22	6	4	22	13	7	22	10
Loam	25	19	8	16	11	6	41	16	8
Silt loam	102	17	9	64	9	6	166	14	9
Silt	4	11	11	3	16	12	7	13	11
Sandy clay	1	24	0	1	10	0	2	17	10
Average for medium soils	135	17	9	88	10	7	223	15	9
Silty clay loam	12	12	5	21	8	12	33	9	5
Clay loam	3	6	11	2	9	4	5	7	8
Silty clay	5	10	7	2	4	4	7	8	7
Clay	3	23	14	10	5	5	13	9	11
Average for fine soils	23	12	8	35	6	4	58	9	7
Land use									
Forest	45	19	9	...	...	...	...	...	...
Old field	21	13	7	...	...	...	...	...	...
Pasture	33	9	6	...	...	...	...	...	...

Table 6.--Average drainage capacity, by volume, for textural groups and land-use categories

Textural group and land use	Surface soils			Subsoils			All soils		
	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation
	No.	- Percent -		No.	- Percent -		No.	- Percent -	
Textural group									
Sand	4	35	9	2	37	3	6	36	7
Loamy sand	2	34	7	1	32	0	3	33	5
Sandy loam	26	31	13	9	30	8	35	31	12
Average for coarse soils	32	32	12	12	31	7	44	32	11
Sandy clay loam	1	13	0	1	9	0	2	11	3
Loam	9	27	13	6	25	15	15	26	13
Silt loam	39	26	12	38	18	13	77	22	13
Average for medium soils	50	25	13	46	20	14	95	23	13
Silty clay loam	8	10	6	9	6	4	17	8	5
Clay loam	2	18	1	2	10	5	4	14	5
Clay	2	6	8	3	3	6	5	4	6
Average for fine soils	14	10	6	15	6	5	29	8	6
Land use									
Forest	45	35	3	...	...	...	...	...	...
Old field	50	19	3	...	...	...	...	...	...
Pasture	31	21	8	...	...	...	...	...	...

ESTIMATION OF BULK DENSITY FROM SOIL PROPERTIES

It is often necessary to express moisture content in inches of water per unit depth of soil. If the bulk density is known, the volumetric moisture content can be calculated by multiplying bulk density by moisture content calculated on a weight basis. The product, multiplied by the depth of soil, expresses moisture as the rainfall equivalent in area-inches.

Owing to its great variation, bulk density is not easy to determine in the field. The swelling and shrinking of soils with addition and loss of water causes some differences, but structure probably accounts for more. Texture, organic content, occurrence of natural hardpans, and disturbances are also influential. In view of the importance of bulk density in soil-moisture studies, and the difficulties involved in its determination, an analysis was made to ascertain if it could be estimated from certain soil properties.

Average bulk-density values by textural class and land use are shown in table 7. There is a consistent increase in bulk density from surface soils to subsoil layers in all textural classes, except silt and sandy clay (these two classes were among those with fewest samples). In general, bulk density was lowest in the silt loams, loams, and other soils of medium texture, higher in the fine-textured soils, and highest in the sandy soils. The average was 1.28 for 319 samples of medium-textured soil, 1.37 for 100 samples of fine texture, and 1.38 for 95 samples of coarse or sandy soil. Standard deviation was slightly less than 0.2 gram per cubic centimeter.

Table 7.--Average soil bulk density, for textural classes and land-use categories

Textural group and land use	Surface soils			Subsoils			All soils		
	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation
	No.	Grams per cc		No.	Grams per cc		No.	Grams per cc	
Textural group									
Sand	8	1.40	0.11	4	1.49	0.04	12	1.43	0.09
Loamy sand	9	1.32	.52	3	1.44	.11	12	1.35	.16
Sandy loam	60	1.36	.21	11	1.42	.18	71	1.36	.20
Average for coarse soils	77	1.36	.20	18	1.44	.15	95	1.38	.19
Sandy clay loam	5	1.35	.15	4	1.36	.29	9	1.36	.21
Loam	45	1.24	.19	27	1.38	.17	72	1.29	.19
Silt loam	138	1.20	.20	89	1.39	.12	227	1.27	.22
Silt	5	1.29	.08	3	1.11	.36	8	1.22	.22
Sandy clay	2	1.50	.27	1	1.49	.00	3	1.50	.19
Average for medium soils	195	1.22	.20	124	1.38	.21	319	1.28	.22
Silty clay loam	23	1.30	.13	26	1.38	.13	49	1.34	.14
Clay loam	9	1.40	.18	6	1.50	.14	15	1.44	.17
Silty clay	5	1.31	.10	2	1.46	.12	7	1.35	.12
Clay	12	1.28	.20	17	1.44	.19	29	1.38	.21
Average for fine soils	49	1.31	.16	51	1.42	.15	100	1.37	.16
Land use									
Forest	67	1.12	.22	...	...	...	...	...	...
Old field	72	1.31	.18	...	...	...	...	...	...
Pasture	47	1.27	.17	...	...	...	...	...	...

Bulk density averaged 1.12 for the surface layers under forest cover, 1.27 for soils under pasture, and 1.31 for old-field soils with herbaceous cover. A substantial number of the samples in the pasture category were from grazed woodlands; the relatively high organic content of these samples probably lowered the bulk-density values for the category.

Single and multiple regressions and correlation coefficients were calculated to relate bulk density to various other soil properties (table 8). Of the factors chosen for analysis only clay content failed to show a highly significant relationship. All significant single correlations except for sand content were negative.

Table 8.--Bulk-density relationships, for surface and subsoil samples combined

Equations 1/	Samples	Independent variable	Mean X	Mean Y	Correlation coefficient	Standard deviation from regression
	No.					
$Y = 1.29 + .0015X_1$	345	S	30	1.33	+.18**	0.184
$Y = 1.46 - .0029X_6$	326	Si	50	1.32	-.31**	.177
$Y = 1.29 + .0015X_2$	326	C	20	1.32	+.10	.185
$Y = 1.47 - .0658X_3$	337	OM	2.64	1.29	-.69**	.149
$Y = 1.78 - .0196X_{11}$	170	PL	24	1.30	-.65**	.157
$Y = 1.44 + .001X_1 + .001X_2 - .010X_3$	...	...	...	...	+.75**	.138
$Y = 1.47 + .001X_1 - .100X_3$	...	...	...	...	+.75**	.138

1/ Y is predicted value.
**Significant at 1-percent level.

Organic content had the highest degree of correlation. Bulk density decreased by .0658 gm per cc. for each increase of one percent in organic matter content. A multiple regression involving sand and organic-matter content improved the prediction. Addition of clay to these other variables had no influence.

Here and in other comparisons, the variables chosen for analysis were those the authors deemed most likely to be related. If more extended analysis had been possible, other variables or combinations might have shown significance.

ESTIMATION OF "WET" MOISTURE CONSTANTS

Moisture held by a core of soil at 0 to 5 cm of water tension approximates the wettest condition of the soil, and when expressed as volume is a measure of total pore space. The 60-centimeter water tension and 1/3-atmosphere pressure are often taken as the upper limit of available soil moisture, or as a moisture content equivalent to the field capacity. These three constants at the "wet end" of the soil-moisture range were analyzed as to their relationships with several other properties. Results are summarized in tables 9, 10, and 11.

Table 9.--Saturation (0-5 cm) relationships, for surface and subsoil samples combined; moisture expressed as percent by volume

Equations 1/	Samples	Independent variable	Mean		Correlation coefficient	Standard deviation from regression
			X	Y		
	No.					
$Y = 49 - .077X_1$	132	S	30	47	-.22*	8
$Y = 42 + .086X_6$	132	Si	54	47	+.21*	8
$Y = 46 + .067X_2$	132	C	16	47	+.09	8
$Y = 42 + 2.099X_3$	132	OM	2.11	47	+.41**	7
$Y = 74 - 21.245X_5$	132	BD	1.27	47	-.59**	7
$Y = 48 - .141X_4$	132	BP	13	47	-.16	8
$Y = 30 + .413X_8$	116	F max	40	47	+.44**	8
$Y = 30 + .688X_{11}$	108	PL	25	48	+.64**	6
$Y = 36 + .315X_{12}$	108	LL	37	48	+.45**	7
$Y = 40 - .052X_1 + .055X_2 + 2.038X_3$	...	...	...	...	+.43**	7
$Y = 77 - .052X_1 - .136X_2 + .281X_3 - 21.16X_5$	...	...	...	...	+.60**	6

1/ Y is predicted value.
* Significant at 5-percent level.
**Significant at 1-percent level.

Table 10.--60-cm relationships, for surface and subsoil samples combined; moisture expressed as percent by volume

Equations 1/	Samples	Independent variable	Mean		Correlation coefficient	Standard deviation from regression
			X	Y		
	No.					
$Y = 45 - .212X_1$	192	S	30	39	-.54**	7
$Y = 29 + .191X_6$	192	Si	52	39	+.44**	7
$Y = 35 + .216X_2$	192	C	18	39	+.30**	8
$Y = 36 + 1.409X_3$	192	OM	1.97	39	+.26**	8
$Y = 52 - 10.203X_5$	192	BD	1.30	39	-.25**	8
$Y = 46 - .563X_4$	192	BP	12	39	-.61**	7
$Y = 19 + .517X_8$	134	F max	39	39	+.59**	6
$Y = 29 + .461X_{11}$	116	PL	26	40	+.48**	6
$Y = 32 + .219X_{12}$	116	LL	38	40	+.37**	7
$Y = 53 - .275X_1 - .090X_6 + 1.182X_3 - 3.014X_5$	...	...	...	...	+.59**	7
$Y = 45 - .314X_1 - .064X_6 + .922X_3 + .324X_4$	...	...	...	...	+.43**	8
$Y = 64 - .194X_1 - .055X_3 - 15.061X_5$	...	...	...	...	+.59**	7
$Y = 44 - .110X_1 + 2.801X_3 - .584X_4$	...	...	...	...	+.81**	5
$Y = 46 - .268X_1 - .076X_6 + 1.446X_3$	...	...	...	...	+.59**	7
$Y = 42 - .210X_1 + 1.352X_3$	...	...	...	...	+.59**	7
$Y = 48 - .140X_1 - .432X_4$	...	...	...	...	+.47**	6

1/ Y is predicted value.
**Significant at 1-percent level.

Table 11. --1/3-atm relationships, for surface and subsoil samples combined; moisture expressed as percent by volume

Equations 1/	Samples	Independent variable	Mean X	Mean Y	Correlation coefficient	Standard deviation from regression
	No.					
$Y = 38 - .312X_1$	126	S	32	28	-.64**	8
$Y = 20 + .148X_6$	126	Si	53	28	+.26**	11
$Y = 16 + .745X_2$	126	C	16	28	+.79**	7
$Y = 28 + .193X_3$	118	OM	2.15	28	+.03	11
$Y = 16 + 9.556X_5$	135	BD	1.30	29	+.18*	11
$Y = 44 - .674X_7$	135	DC	22	29	-.81**	7
$Y = 28 + .130X_{11}$	107	PL	24	31	+.09	10
$Y = 14 - .167X_1 + .580X_2 + .130X_3 + 7.248X_5$	...	...	...	...	+.85**	6

1/ Y is predicted value.
* Significant at 5-percent level.
**Significant at 1-percent level.

In the regressions with sand content, the correlation coefficient was lowest for the 0-5 centimeter values and highest for the 1/3-atmosphere constants. The correlation coefficient of the silt factor was highest for the 60-centimeter constant. The clay factor was non-significant at 0-5 centimeters but highly significant in the 60-centimeter and 1/3-atmosphere comparisons. The correlations for sand content were negative, while those for silt and clay were positive.

The relationships with soil organic matter were highly significant at 0-5 centimeter and 60-centimeter tensions but non-significant at 1/3-atmosphere pressure. These relations were positive. Highly significant negative relationships were found between bulk density and 0-5 centimeter and 60-centimeter tensions; the relation with 1/3-atmosphere pressure was significant and positive.

There was a highly significant positive correlation between 0-5 cm tension and field maximum, plastic limit, and liquid limit. The relationship between 0-5 cm tension and big pores was non-significant, but when moisture tension was increased to 60-cm the correlation became highly significant. An interesting point in the correlation between field maximum and 60-cm tension was that the mean values of the 134 samples were 39 percent by volume for each variable. The relationships between plastic limit and 0-5 cm tension and 60-cm tension were significant at the one-percent level, but plastic limit was not significantly related to 1/3-atmosphere tension.

Several combinations of soil variables were used in multiple regressions in an attempt to reduce the standard deviations. For the 0-5 cm or saturation constant, a combination of the effects of sand, clay, and organic matter failed to reduce the standard deviation below that of organic matter alone. Adding one more variable, bulk density, reduced the standard deviation slightly.

The multiple regression with the highest degree of significance for the 60-centimeter relationships was a combination of sand content, organic

matter, and big pores. The standard deviation from the regression was 5 percent, less than any of the single-factor deviations.

A multiple regression of 1/3-atmosphere moisture on 4 independent variables--sand, clay, organic matter, and bulk density--was slightly better than any single regression.

In a further test of these relationships, thirty samples, representing the entire textural range and a variety of parent materials, were selected at random from a large group of southern soils for which 0-5 and 60-centimeter moisture had been determined. The mean difference of these 30 determined values from the estimated values was computed (table 12). Here again, 0-5 cm moisture (saturation) was estimated with fair accuracy from bulk density alone. Moisture content at 60-centimeter tension was best estimated from sand, among the single variables; but the estimate was improved when sand, organic matter, and bulk density were used in conjunction.

Table 12.--Differences, in percent by volume, between estimated and actual values of saturation and 60-cm moisture

Methods of estimation	Average estimated values		Mean differences from actual values	
	Saturation	60-cm.	Saturation	60-cm.
Textural group mean	45.3	36.2	6.6	5.6
Sand	45.4	35.2	6.7	4.8
Silt	...	34.4	...	6.8
Clay	47.3	...	8.0	...
Organic matter	45.8	37.9	7.4	8.9
Bulk density	42.1	35.5	3.9	7.8
Plastic limit	44.9	37.9	5.2	5.4
Sand, clay, organic matter, bulk density	40.2	...	4.4	...
Sand, organic matter, bulk density	...	32.7	...	4.5
Sand, organic matter, big pores	...	37.9	...	5.7
Average	41.7	33.8	...	...

While scarcity of data prevented the inclusion of moisture equivalent in the regressions, the relationship between this value and 1/3-atmosphere is suggested in figures 2 and 3.

ESTIMATION OF 15-ATMOSPHERE CONSTANT

Moisture content of the soil at 15-atmospheres tension is widely used to delineate the lower limit of water available for plant growth. Because of the general utility of this value, an attempt was made to develop equations to predict it from various other soil properties, singly and in combination. The properties used in the analysis were field minimum moisture, bulk density, and percentages of sand, silt, clay, and organic matter.

The close relationship between 15-atmosphere values and wilting-point is generally recognized. Lack of data prevented regression analysis of these two values, but available information is summarized in figure 6. In this chart, 15-atmosphere values average about the same as those for wilting point in coarse and medium soils but go slightly higher in the fine-textured soils. For most texture classes wilting-point values were above those for field minimum.

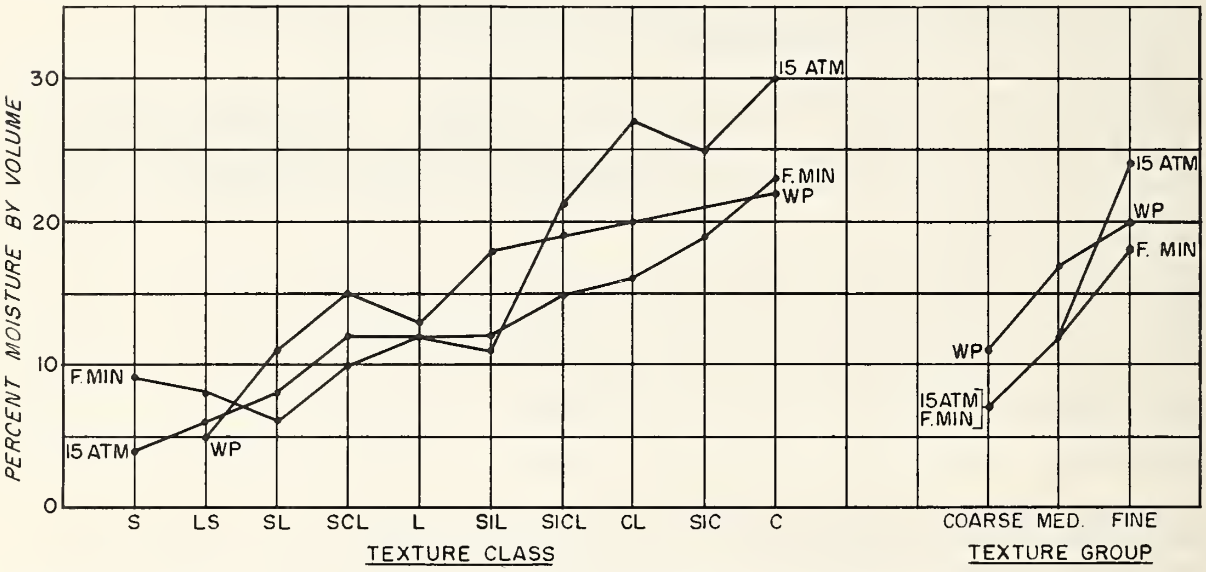

Figure 6.--*Variation of three "dry" moisture constants with soil texture.*

The relationships of 15-atmosphere moisture and silt, organic matter, and bulk density were not significant (table 13). Those for sand and clay content, and for field minimum, were highly significant. The smallest standard deviation from regression was 4 percent by volume for the clay variable. Two multiple regressions did not reduce the standard error of estimate below that for the single regression on clay.

A separate correlation was attempted between 15-atmosphere moisture and liquid limit. Here the 15-atmosphere value, as well as liquid limit, was expressed as percent by weight, rather than by volume. Though liquid limit is not a "dry end" constant, it approximates saturation

Table 13.--15-atm relationships, for surface and subsoil samples combined; moisture in percent by volume

Equations 1/	Samples	Independent variable	Mean		Correlation coefficient	Standard deviation from regression
			X	Y		
	No.					
$Y = 18 - .145X_1$	241	S	31	13	-.43**	7
$Y = 15 - .029X_6$	241	Si	50	13	-.08	7
$Y = 4 + .483X_2$	246	C	19	14	+.84**	4
$Y = 12 + .543X_3$	236	OM	1.96	13	+.11	7
$Y = 12 + 1.276X_5$	241	BD	1.33	13	+.03	7
$Y = 4 + .815X_9$	130	F min	12	14	+.73**	5
$Y = -7 + .265X_1 + .504X_2 + 1.121X_3 - 068X_5$	...	...	...	...	+.68**	5
$Y = 2 + .463X_2 + 1.115X_3$	...	...	...	...	+.84**	4

1/ Y is predicted value.
**Significant at 1-percent level.

percentage, which in turn has been useful as an indication of water-holding capacity and texture[3]. The regression equation was $Y = -2.0 + .36X_{12}$ where Y is 15-atmosphere moisture and X_{12} is liquid limit. The correlation coefficient, +.85, was significant at the one-percent level. The standard deviation of the regression was 2.9

[3] Wilcox, L.V.
1951. *A method for calculating the saturation percentage from the weight of a known volume of saturated soil paste.* Soil Sci. 72: 233-237, illus.

ESTIMATION OF AVAILABLE WATER CAPACITY

Data on available water capacity, as calculated by various methods, were tabulated to indicate the relationship of this constant to soil texture and land use. An attempt was also made to estimate available water capacity from other soil properties.

Four methods of calculating available water capacity were used:

(1) Determining the field moisture index, or the difference between field maximum and field minimum.
(2) Subtracting the water held at 15-atmospheres pressure from the water retained at 60-centimeters tension.
(3) Subtracting the 15-atmosphere value from the 1/3-atmosphere value.
(4) Subtracting wilting point from the field capacity.

Table 14 shows average values for each textural class and land-use category. Both in surface and subsoil, medium-textured soils tended to be highest in available water capacity and coarse-textured soils lowest.

In general, the first method of determination--field maximum less field minimum--gave the highest values. Capacities obtained by subtracting 15-atmosphere from 60-centimeter values usually were next highest.

In determinations by the first two methods, medium-textured soils tended to have the greatest water capacity, and coarse-textured soils the least. These relationships did not follow this pattern in the 1/3- and 15-atmosphere comparisons, nor in the field capacity-wilting point determinations. The authors attributed these differences to seemingly high wilting-points for some samples from medium soils, and to high 1/3-atmosphere values for some fine soils. The high 1/3-atmosphere values were from sieved or disturbed material. There was no explanation for the high wilting-point values, except perhaps the authors' predilections.

Samples of known bulk density were used to compute available water capacity on a volumetric basis. The values in table 15 are presented as inches of available water capacity per inch of soil for each textural class, so that they can be used to derive water capacity for any depth of soil. In figure 7, these data are averaged by texture groups. This chart and table 15 illustrate the same general moisture-capacity trends noted in table 14.

The capacities obtained by subtracting 15-atmosphere values from 60-centimeter values were correlated with several soil properties. This method was chosen because the authors believed that the 60-centimeter determination closely approximated the upper limit of available water for all textural classes. The best estimate of available water capacity was obtained from silt content and field moisture index (table 16). Highly significant correlations were also obtained with clay, bulk density, field maximum, field minimum, plastic limit, and liquid limit.

Table 14. --Average available water capacity, percent by weight, as determined by 4 methods

Textural group and land use	Surface soils			Subsoils			All soils		
	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation	Samples	Mean	Standard deviation
	No.	- Percent -		No.	- Percent -		No.	- Percent -	
FIELD MAXIMUM MINUS FIELD MINIMUM									
Textural group									
Sand	2	12	2	2	7	1	4	10	3
Loamy sand	1	13	0	1	9	0	2	11	3
Sandy loam	18	19	9	7	15	3	25	18	8
Average for coarse soils	21	18	9	10	13	4	31	16	8
Sandy clay loam	1	25	0	3	19	4	4	20	4
Loam	11	26	7	10	17	5	21	21	8
Silt loam	42	28	11	40	23	9	82	26	10
Average for medium soils	55	28	10	54	22	10	109	25	10
Silty clay loam	9	20	4	5	18	4	14	19	4
Clay loam	4	22	4	2	8	1	6	18	8
Silty clay	2	20	2	2	14	5	4	17	5
Clay	4	19	8	7	14	5	11	16	6
Average for fine soils	19	20	5	16	14	5	35	18	5
Land use									
Forest	21	28	9	...	...	...	...	...	...
Old field	25	29	6	...	...	...	...	...	...
Pasture	23	31	6	...	...	...	...	...	...
60-CENTIMETERS TENSION MINUS 15 ATMOSPHERES									
Textural group									
Sand	4	11	8	4	7	3	8	9	6
Loamy soils	2	18	6	1	18	0	3	18	4
Sandy loam	9	16	5	4	22	6	13	18	6
Average for coarse soils	15	15	6	9	15	9	24	15	7
Sandy clay loam	...	...	...	4	12	4	4	12	4
Loam	17	22	7	15	19	7	32	21	7
Silt loam	57	25	9	54	21	9	111	23	9
Average for medium soils	75	25	8	74	20	9	149	23	9
Silty clay loam	4	16	3	14	14	4	18	14	4
Clay loam	3	16	7	2	10	6	5	14	6
Silty clay	5	17	7	2	11	1	7	15	6
Clay	1	8	0	7	14	7	8	13	7
Average for fine soils	13	16	6	25	13	5	38	14	5
Land use									
Forest	36	26	6	...	...	...	...	...	...
Old field	21	27	5	...	...	...	...	...	...
Pasture	33	27	7	...	...	...	...	...	...
1/3-ATMOSPHERE TENSION MINUS 15 ATMOSPHERES									
Textural group									
Sand	11	4	3	2	2	1	13	4	3
Loamy sand	8	4	3	1	2	0	9	4	3
Sandy loam	16	10	6	8	10	4	24	10	5
Average for coarse soils	35	7	5	11	8	5	46	7	5
Sandy clay loam	1	21	0	1	9	0	2	15	8
Loam	16	12	3	7	10	2	23	11	3
Silt loam	63	16	7	38	14	4	101	15	6
Average for medium soils	81	15	6	47	13	5	128	15	6
Silty clay loam	5	16	7	9	13	2	14	14	4
Clay loam	6	14	5	3	11	4	9	13	5
Silty clay	5	17	9	1	12	0	6	16	8
Clay	7	21	8	12	18	8	19	19	8
Average for fine soils	23	17	7	25	15	6	48	16	7
Land use									
Forest	23	13	7	...	...	...	...	...	...
Old field	33	19	6	...	...	...	...	...	...
Pasture	19	13	4	...	...	...	...	...	...
FIELD CAPACITY MINUS WILTING POINT									
Textural group									
Sand	2	6	2	...	...	...	2	6	2
Loamy sand	7	7	2	2	8	0	9	7	2
Sandy loam	10	11	2	5	10	4	15	11	3
Average for coarse soils	19	9	3	7	9	4	26	9	3
Sandy clay loam	1	12	0	1	6	0	2	9	4
Loam	4	13	2	5	13	2	9	13	2
Silt loam	1	17	0	1	15	0	2	16	1
Average for medium soils	6	14	3	8	12	4	14	13	3
Silty clay loam	9	13	2	2	18	2	11	14	2
Clay loam	8	14	4	2	14	8	10	14	4
Silty clay	...	...	...	...	...	...	...	...	...
Clay	39	16	3	9	11	3	48	15	4
Average for fine soils	56	15	4	13	13	4	69	15	4

Table 15.--Available water capacity in inches per inch of soil

Soil texture	Field moisture index		60-cm minus 15-atm		1/3-atm minus 15-atm		Field capacity minus wilting point	
	Surface	Subsoil	Surface	Subsoil	Surface	Subsoil	Surface	Subsoil
Sand	0.16	0.10	0.15	0.10	0.08	0.03	...	...
Loamy sand	.21	.14	.27	.27	.05	.04	0.09	0.10
Sandy loam	.25	.20	.22	.29	.15	.12	.20	.16
Sandy clay loam	.29	.23	...	.16	...	.13	.18	.16
Loam	.29	.21	.26	.25	.12	.12	.16	.17
Silt loam	.32	.28	.30	.27	.19	.19	.16	...
Sandy clay	...	...	...	...	.27	...	...	.08
Silt	.30	.40	.34	.34	...	.20	...	...
Silty clay loam	.28	.25	.21	.20	.18	.18	...	...
Clay loam	.28	.14	.22	.15	.10	.12	.18	...
Silty clay	.26	.20	.21	.17	.18	.17	...	...
Clay	.25	.20	.12	.21	.37	.18	.23	...

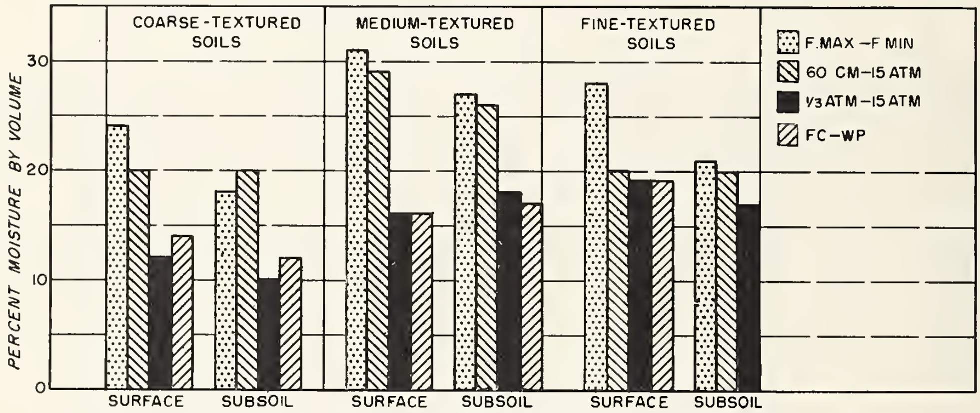

Figure 7.--*Available water capacities, by four methods of determination.*

Table 16.--Available water capacity relationships (60-cm minus 15-atm), for surface and subsoil samples combined; moisture expressed as percent by volume

Equations 1/	Samples	Independent variable	Mean X	Mean Y	Correlation coefficient	Standard deviation from regression
	No.					
$Y = 28 - .072X_1$	120	S	31	26	-.20*	7
$Y = 16 + .189X_6$	120	Si	52	26	+.51**	6
$Y = 31 - .300X_2$	120	C	17	26	-.48**	7
$Y = 25 + .523X_3$	120	OM	2.10	26	+.11	8
$Y = 39 - 10.326X_5$	120	BD	1.26	26	-.30**	7
$Y = 28 - .136X_4$	120	BP	14	26	-.16	7
$Y = 17 + .229X_8$	120	F max	39	26	+.26**	7
$Y = 31 - .445X_9$	120	F min	12	26	-.38**	7
$Y = 12 + .524X_{10}$	120	FMI	27	26	+.56**	6
$Y = 18 + .298X_{11}$	105	PL	26	26	+.28**	7
$Y = 33 - .184X_{12}$	105	LL	38	26	-.29**	7

1/ Y is predicted value.
* Significant at 5-percent level.
**Significant at 1-percent level.

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